NAVORD REPORT 2891

CRATER FORMATION BY SHALLOW UNDERWATER EXPLOSIONS
AT DAHLGREN VIRGINIA

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U. S. NAVAL ORDNANCE LABORATORY
WHITE OAK, MARYLAND

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INTERIM REPORT NO. 8

NOL Project 152

AFSWP-263

CRATER FORMATION BY SHALLOW UNDERWATER EXPLOSIONS AT DAHLGREN, VIRGINIA

by

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ABSTRACT: The dimensions of craters formed by shallow underwater explosions on clay, sand, sandy clay and silt bottoms are presented. The data are not extensive but indicate that cratering by atomic weapons could probably close an average harbor to navigation for a considerable period of time.

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This report presents a summary of crater measurements made from charges fired in a study of surface phenomena for the Armed Forces Special Weapons Project under Task NOL-152. Because this program was not set up primarily for the study of craters, the range of firing conditions in different soil types was not extensive. However, it is believed that the measurements given here will be useful in studies of cratering, particularly when combined with other data. The report is intended for information only. Any opinions expressed herein are those of the author.

EDWARD L. WOODYARD
Captain, USN

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By direction

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CHAPTER I

EXPERIMENTAL PROGRAM

1.1 Introduction. As part of the experimental study of the base surge under Task NOL-152, five series of explosion tests in shallow water were fired at the U. S. Naval Proving Ground in Dahlgren, Virginia during 1950, 1951 and 1952. In the first group of tests it was noted that charges fired on a clay bottom produced large craters with lips that extended above the water surface and persisted for long periods of time. As some of the high explosive tests were scaled geometrically to a nominal atomic bomb detonated at an average harbor depth, the results indicated that cratering by atomic weapons could seriously hinder harbor navigation.

The urgent need for more detailed knowledge of underwater cratering led to the initiation of an experimental program at the Waterways Experiment Station in Vicksburg, Mississippi in 1951[1]* with the study of craters as one of its major objectives.

The NOL programs were conducted primarily to obtain data on the scaling of surface phenomena from shallow underwater explosions. However, they provided an opportunity to obtain useful crater measurements from relatively large TNT explosions. The results are only summarized herein and a detailed analysis is not attempted, but some discussion is presented in order to avoid possible misinterpretation of the data.

1.2 Experimental Procedure. TNT charges weighing 100 lb, 600 lb, 3600 lb, and 4200 lb were fired in water depths ranging from zero to 9.25 feet. The majority of charges were placed on the river bottom, but some were partly buried and some were supported on wooden platforms, usually to obtain a charge position at mid-depth. Charge depth, c, was measured from the water surface to the center of the charge.

*Such numbers refer to the list of references at the end of this report.

A 100 lb charge consisted of two 50 lb Mark 14 demolition blocks strapped together to form a cube, about 13 inches on each side. Thus, the center of the cube was 0.54 ft above the bottom side.

The 600 lb charges were Mark VII depth charges which are 24-7/8 inches wide and 27-5/8 inches long. The total length of the casing includes rims about one inch high, which sank into the bottom when the charges were placed on end for firing. On bottom shots the center was considered to be 1.07 ft above the river bottom.

The 3600 and 4200 lb charges consisted of 6 or 7 Mark VII depth charges with the central charge encircled horizontally by the others. Therefore, charge heights were the same as for the 600 lb charges but diameters were about three times as large.

For comparison of charges of different weights, a scaled depth, λ_c, was used:

$$\lambda_c = \frac{c}{W^{1/3}}$$

where c = depth to center of charge, ft
W = weight of charge, lb (TNT)

1.3 Crater Measurements. Three measurements were made on each crater. Crater width, or diameter, w, was measured inside the top of the lip. Crater depth, d, was measured below the level of the original bottom, and lip height, h, was measured above the level of the original bottom. In addition, profiles of six of the craters on clay bottoms were obtained.

Horizontal measurements were made with a brass measuring chain and vertical dimensions were obtained with sounding poles. Individual measurements were probably accurate to 0.1 ft, but the craters were usually not entirely visible beneath the water surface and were somewhat irregular in shape. This led to some uncertainty in the assignment of values. In general, the results presented are considered to have a possible error of $\pm$ 0.5 feet.

Mean lip heights are given, but the values of crater width and depth are maxima.

Four different soil types were distinguished in the firing area at Dahlgren: clay, sand, a mixture of clay and sand, and silt. The crater measurements obtained with the four different bottom conditions are listed in Tables I, II, III and IV. The last column, h/D, the ratio of lip height to water depth, indicates the effectiveness of cratering as an obstruction to navigation. Craters that formed in the soft silt in relatively deep water were very poorly defined and the measurements are of doubtful reliability.

The profiles of four 600 lb and two 4200 lb bottom shots on clay are presented in Figures 1 and 2.

1.4 <u>Persistence of Craters</u>. The long persistence of crater lips in clay represents a particular hazard of explosions in this type of soil. The clay craters are also very slow in filling in. The ratios of lip height to water depth (h/D) shown in the tables indicate that if crater sizes obtained in clay can be extrapolated to nuclear weapons in an average harbor (30-40 ft deep), navigation can be effectively blocked for a considerable period of time.

The lips of the craters in clay contained large cracks and were sometimes pockmarked by stones. Figure 3 shows two clay craters formed by 100 lb explosions. Distant and close-up views of the crater formed by a 4200 lb explosion on clay are given in Figure 4.

Explosions in a mixture of clay and sand formed craters with chunky lips, which disappeared in from one to two weeks. Two examples of this type of crater are shown in Figure 5. The lips formed on sand craters collapsed rapidly after the explosion and the craters filled in at a relatively high rate. The crater formed by a 100 lb charge in 1 ft of water on a sand bottom is shown in Figure 6.

It was possible to remeasure some of the craters several months after formation and the data obtained are summarized in Table V. Figure 7 shows the appearance of the crater from Shot 281 about 49 days after formation and the crater from Shot 272 at 86 days after formation.

TABLE I UNDERWATER CRATER FORMATION IN CLAY

Shot No.	Charge Weight W (lb)	Charge Position	Water Depth D (ft)	Charge Depth c (ft)	Scaled Charge Depth λ_c (ft/lb$^{1/3}$)	Crater Width w (ft)	Crater Depth d (ft)	Lip Height h (ft)	h/D
306	100	Bottom	0.50	-0.04	-0.009	18.0	5.1	2.2	4.40
307	100	Bottom	1.00	0.46	0.099	24.0	5.5	2.5	2.50
308	100	Bottom	1.50	0.96	0.207	24.9	5.8	2.8	1.87
309	100	Bottom	2.00	1.46	0.315	23.0	5.4	2.8	1.40
315	100	Bottom	2.08	1.54	0.332	24.7	5.1	3.1	1.49
310	100	Bottom	2.96	2.42	0.522	26.7	6.3	2.8	0.94
305	100	Bottom	3.92	3.38	0.728	20.0	2.5	0.5	0.12
304	100	Bottom	5.06	4.52	0.974	22.1	5.3	0.8	0.16
278	600	Bottom	2.17	1.10	0.130	41.0	11.2	3.8	1.75
285	600	Bottom	2.27	1.20	0.142	35.0	9.7	4.0	1.76
272	600	Bottom	3.42	2.35	0.278	40.7	4.3	4.5	1.32
212	600	Bottom	4.08	3.01	0.357	32.0	8.0	2.0	0.49
213	600	Bottom	4.83	3.76	0.446	34.0	10.5	2.5	0.52
271	600	Platform	4.25	2.00	0.237	40.5	5.8	4.3	1.01
216	600	Platform	4.38	2.17	0.257	32.0	9.0	1.0	0.23
273	600	Platform	4.50	2.25	0.267	43.0	10.0	3.0	0.67
281	4200	Bottom	2.17	1.10	0.068	70.0	15.5	4.0	1.84
112	4200	Bottom	2.50	1.43	0.089	65.0	9.5	7.0	2.40
114	4200	Bottom	3.42	2.35	0.146	60.0	9.5	7.0	2.05
218	4200	Bottom	4.00	2.93	0.182	70.0	14.0	6.0	1.50
275	4200	Bottom	4.29	3.22	0.200	75.0	8.9	5.0	1.17
215	4200	Bottom	4.33	3.26	0.202	65.0	15.8	5.4	1.25
300	4200	Bottom	5.14	4.06	0.252	77.6	6.5	3.0	0.58
217	4200	Bottom	8.58	7.51	0.465	75.0	14.5	5.0	0.58
219	4200	Bottom	8.92	7.85	0.487	69.0	16.0	2.0	0.22
221	4200	Bottom	9.25	8.57	0.531	74.0	13.0	5.5	0.59
111	4200	Platform	7.83	4.00	0.248	--	3.0	1.0	0.13
113	4200	Platform	8.00	4.00	0.248	80.0	10.0	3.0	0.38
276	4200	Platform	8.25	4.35	0.270	70.0	12.8	1.5	0.18
222	4200	Platform	8.50	4.67	0.289	30.0	3.0	0	0

TABLE II UNDERWATER CRATER FORMATION IN SANDY CLAY

Shot No.	Charge Weight W (lb)	Charge Position	Water Depth D (ft)	Charge Depth c (ft)	Scaled Charge Depth λ_c (ft/lb$^{1/3}$)	Crater Width w (ft)	Crater Depth d (ft)	Lip Height h (ft)	h/D
284	600	Bottom	1.00	-0.07	-0.008	28.0	7.0	2.0	2.00
283	600	Bottom	1.83	0.76	0.090	30.0	6.0	1.2	0.66
282	600	Bottom	2.50	1.43	0.169	34.0	7.5	1.5	0.60
299	600	Buried	2.13	1.82	0.216	34.3	3.8	1.5	0.75
280	4200	Bottom	1.83	0.76	0.047	58.0	9.0	2.5	1.37
296	4200	Buried	2.25	1.36	0.084	64.0	8.4	3.5	1.56
293	4200	Buried	2.52	1.63	0.101	65.3	8.5	3.0	1.19
295	4200	Buried	2.04	2.28	0.141	67.6	8.8	3.0	1.47
294	4200	Buried	2.65	2.50	0.155	63.6	7.8	3.0	1.13
297	4200	Buried	2.94	2.59	0.161	59.0	7.7	2.3	0.78
298	4200	Buried	4.38	3.80	0.235	63.3	3.3	3.8	0.87

TABLE III UNDERWATER CRATER FORMATION IN SAND

Shot No.	Charge Weight W (lb)	Charge Position	Water Depth D (ft)	Charge Depth c (ft)	Scaled Charge Depth λ_c (ft/lb$^{1/3}$)	Crater Width w (ft)	Crater Depth d (ft)	Lip Height h (ft)	h/D
314*	100	Bottom	0	-0.54	-0.116	13.3	3.3	1.0	--
311	100	Bottom	1.00	0.46	0.099	17.4	2.2	1.0	1.00
312	100	Bottom	2.00	1.46	0.315	19.9	3.0	0.4	0.20
313	100	Bottom	3.00	2.46	0.530	21.3	3.5	1.3	0.43
214	4200	Bottom	4.33	3.26	0.202	64.0	12.0	2.0	0.46

*Fired on wet sand

TABLE IV UNDERWATER CRATER FORMATION IN SILT

Shot No.	Charge Weight W (lb)	Charge Position	Water Depth D (ft)	Charge Depth c (ft)	Scaled Charge Depth λ_c (ft/lb$^{1/3}$)	Crater Width w (ft)	Crater Depth d (ft)	Lip Height h (ft)	h/D
303	3600	Platform	8.42	5.28	0.345	--	0.7	1.3	0.15
279	4200	Platform	8.58	4.90	0.304	--	9.5	0.5	0.06
302	4200	Platform	8.77	5.42	0.336	--	1.7	0.3	0.03

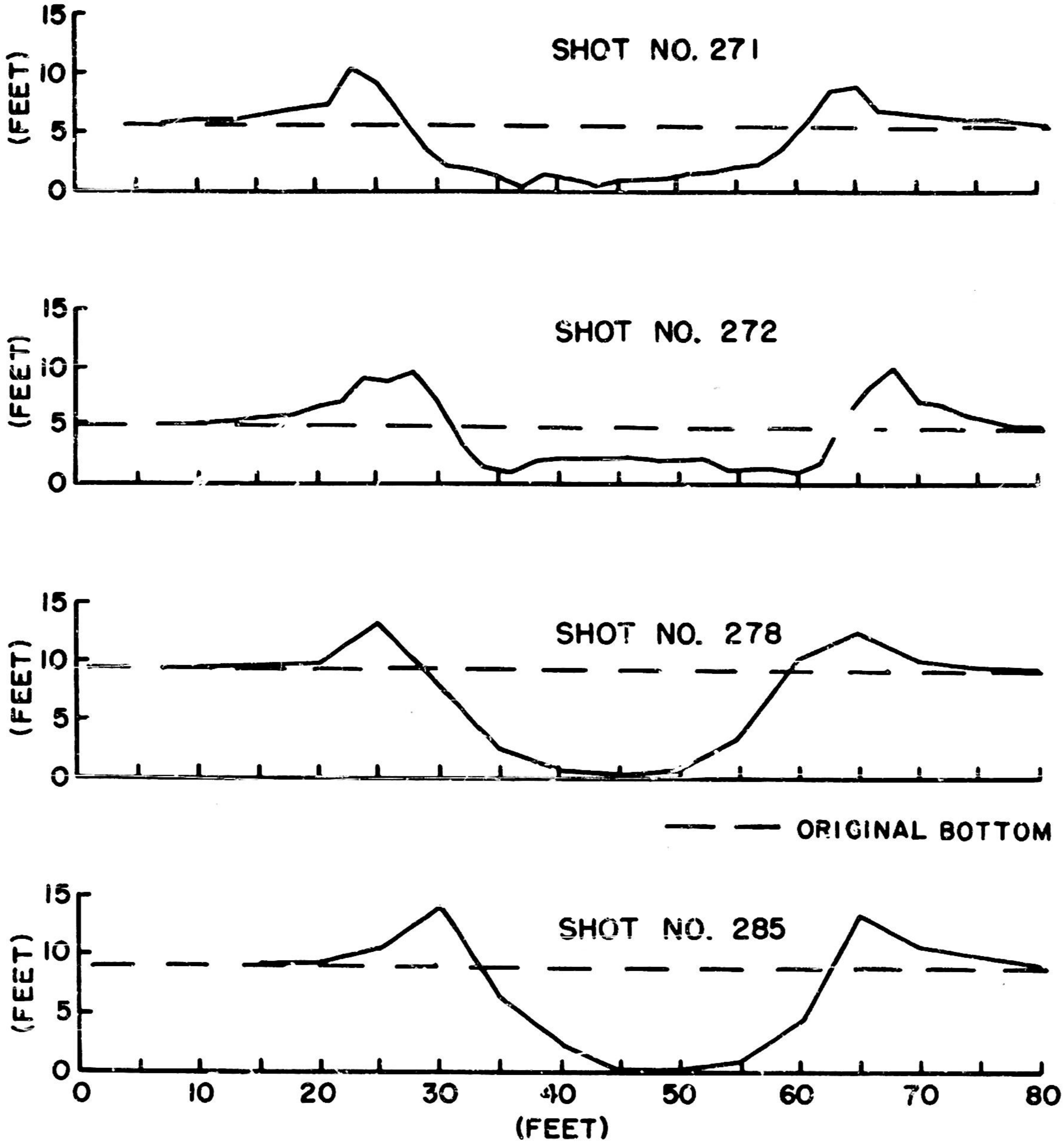


FIG. 1 PROFILES OF CRATERS FORMED BY 600 LB CHARGES ON CLAY

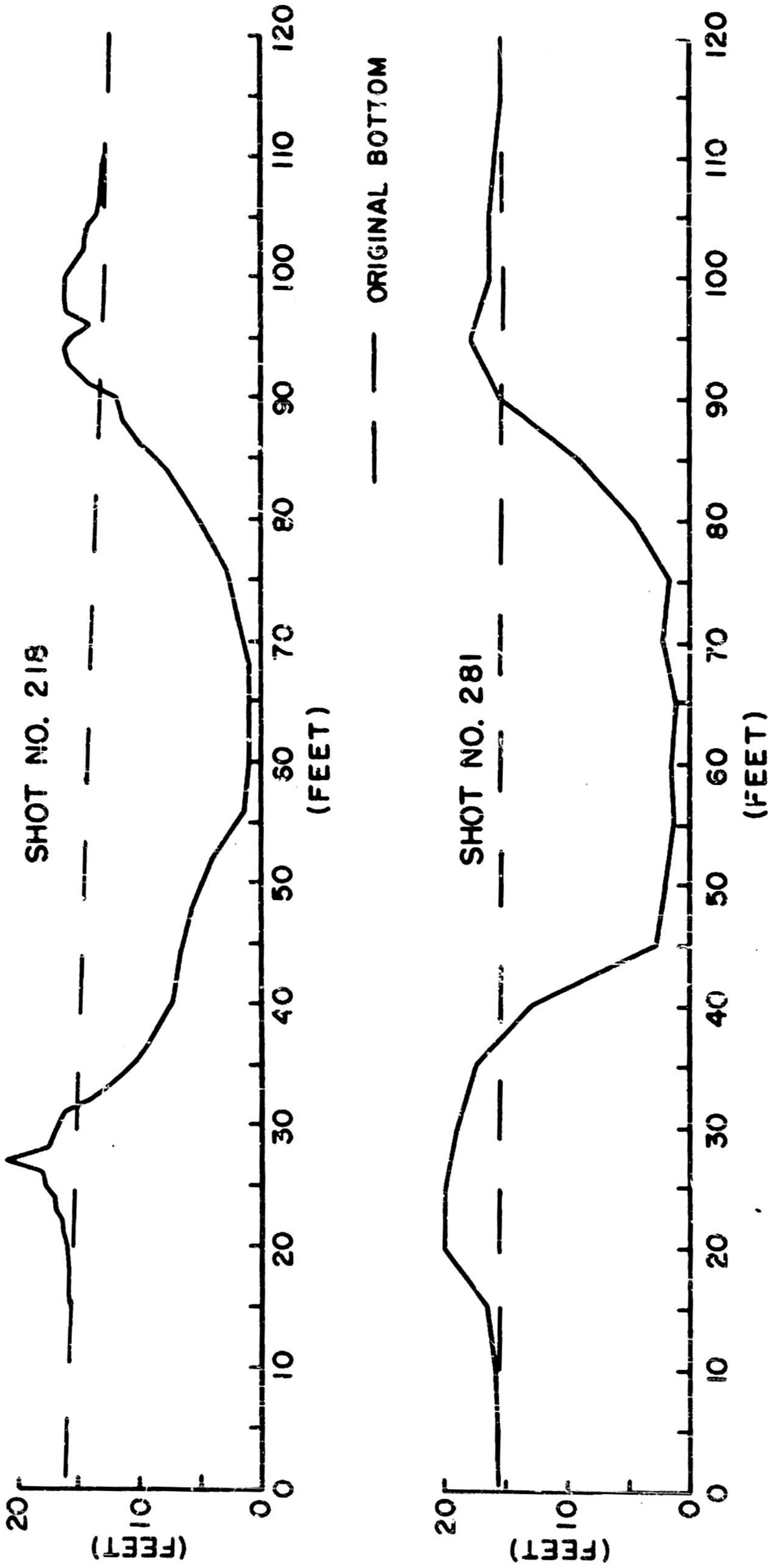
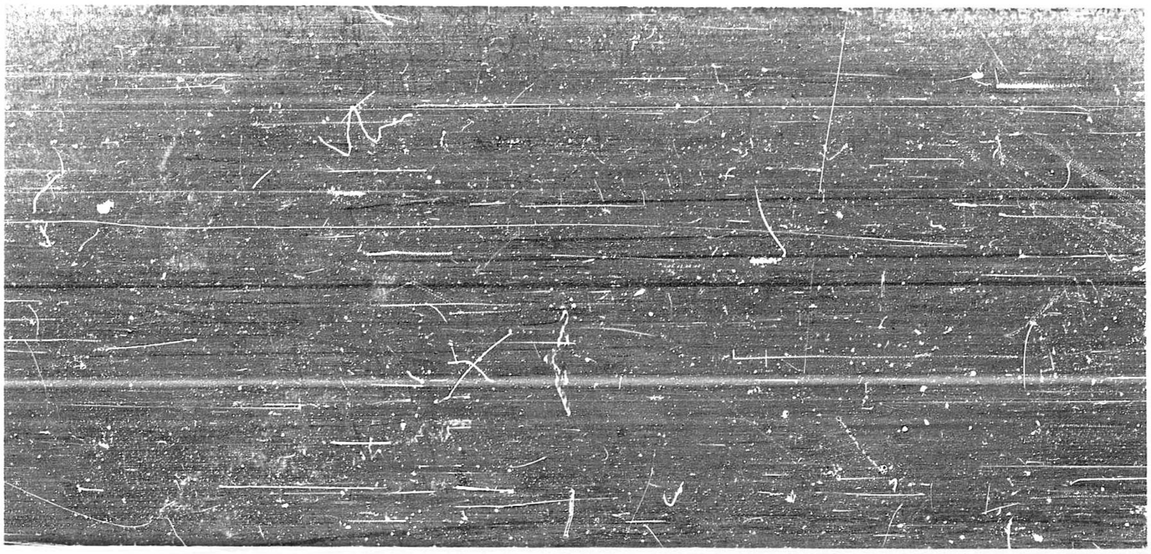
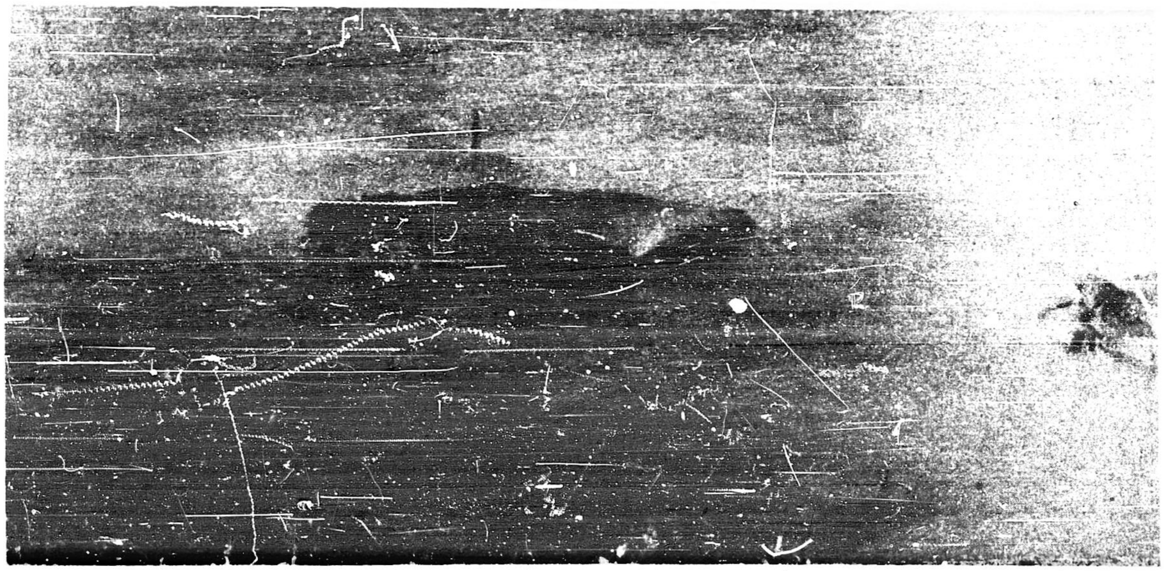


FIG. 2 PROFILES OF CRATERS FORMED BY 4200 LB CHARGES ON CLAY



SHOT NO. 307 WATER DEPTH 1.00 FT

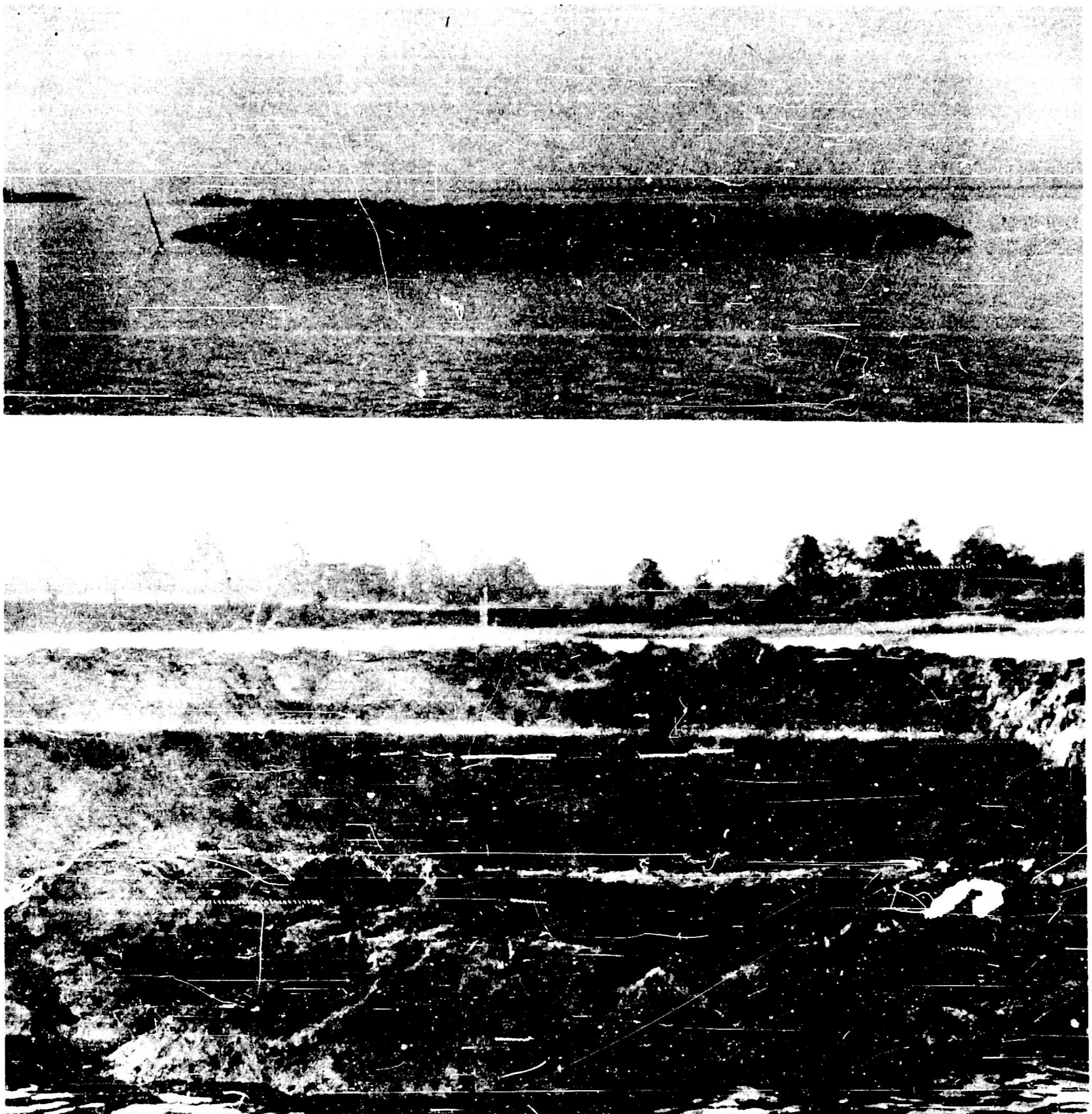
CHARGE ON BOTTOM



SHOT NO. 309 WATER DEPTH 2.00 FT

CHARGE ON BOTTOM

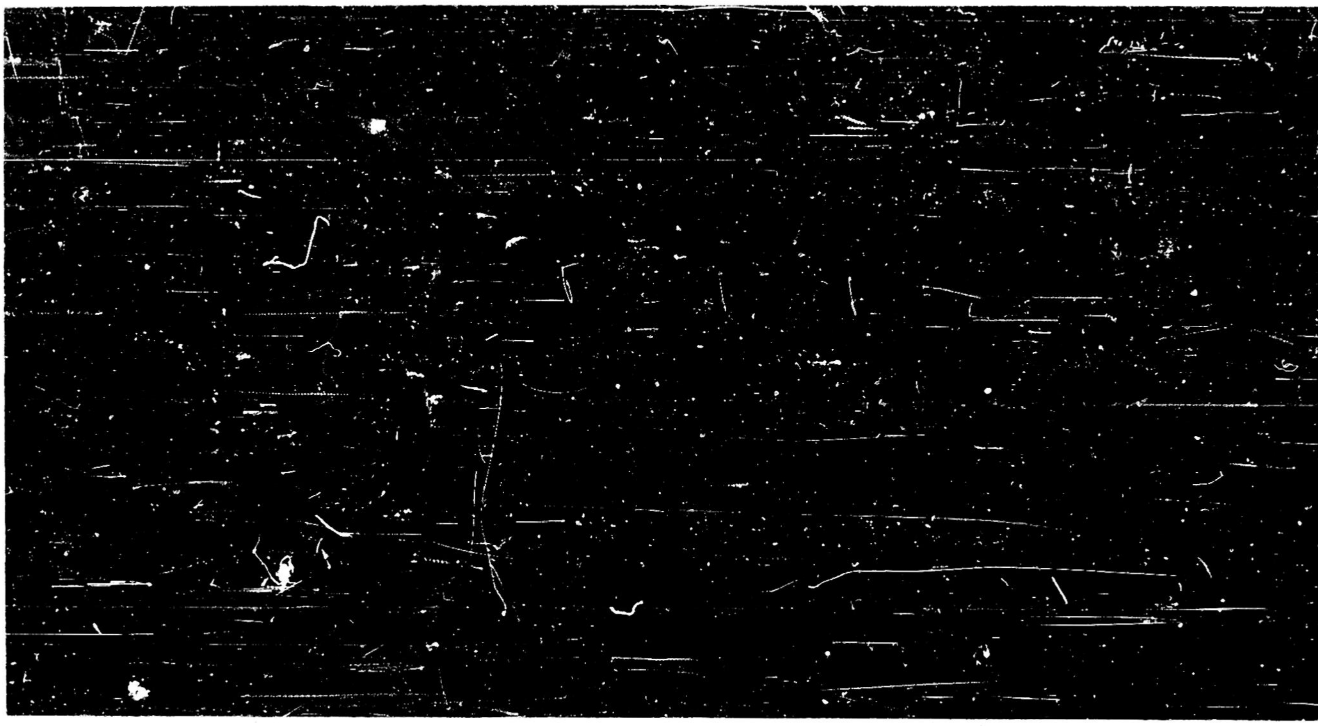
FIG. 3 CRATERS FORMED BY 100 LB CHARGES ON CLAY



SHOT NO. 218 CHARGE ON BOTTOM WATER DEPTH 4.00 FT

FIG. 4

VIEWS OF CRATER FORMED BY 4200 LB CHARGE ON CLAY

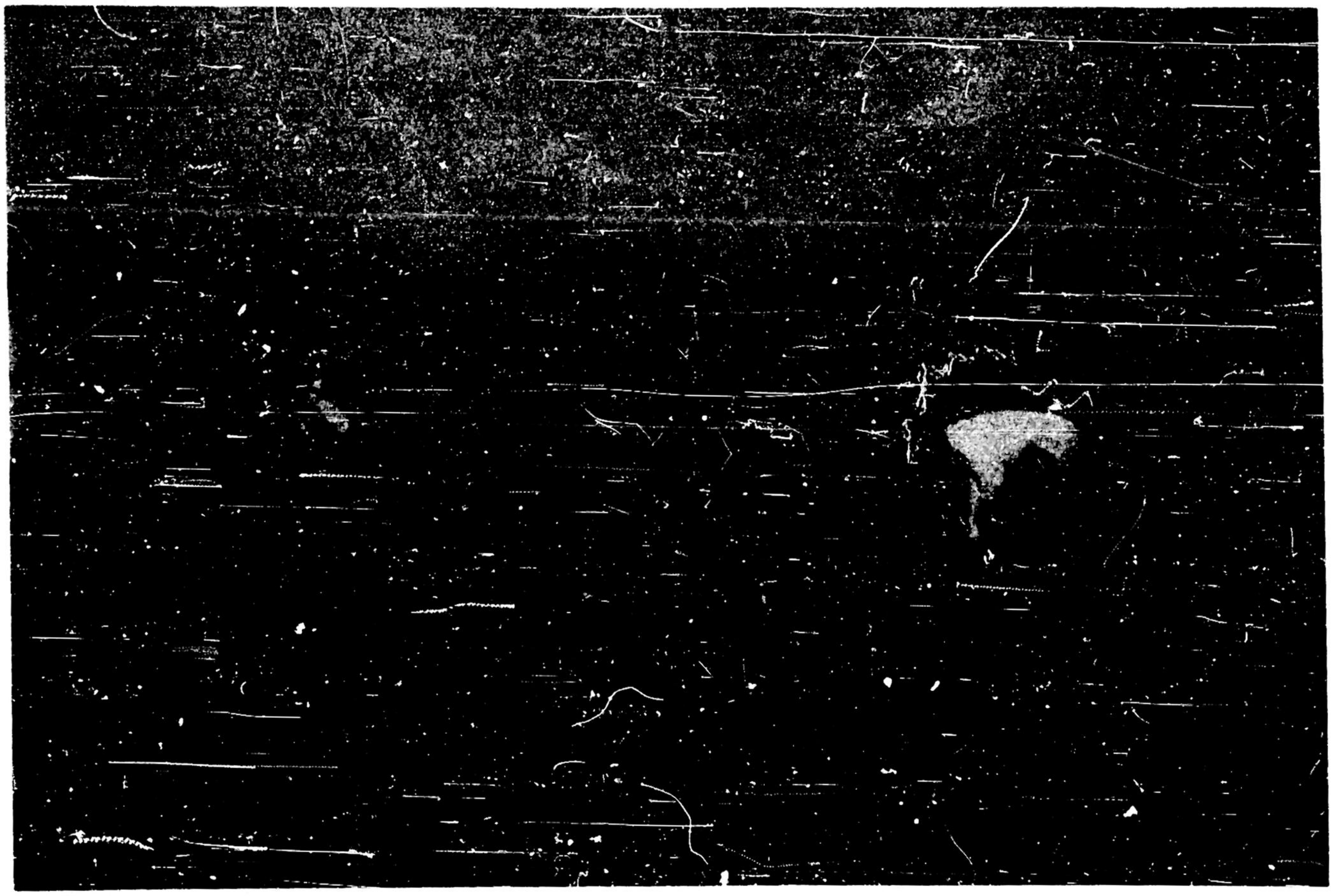


SHOT NO. 293 CHARGE PARTLY BURIED WATER DEPTH 2.52 FT

SHOT NO. 294 CHARGE PARTLY BURIED WATER DEPTH 2.65 FT

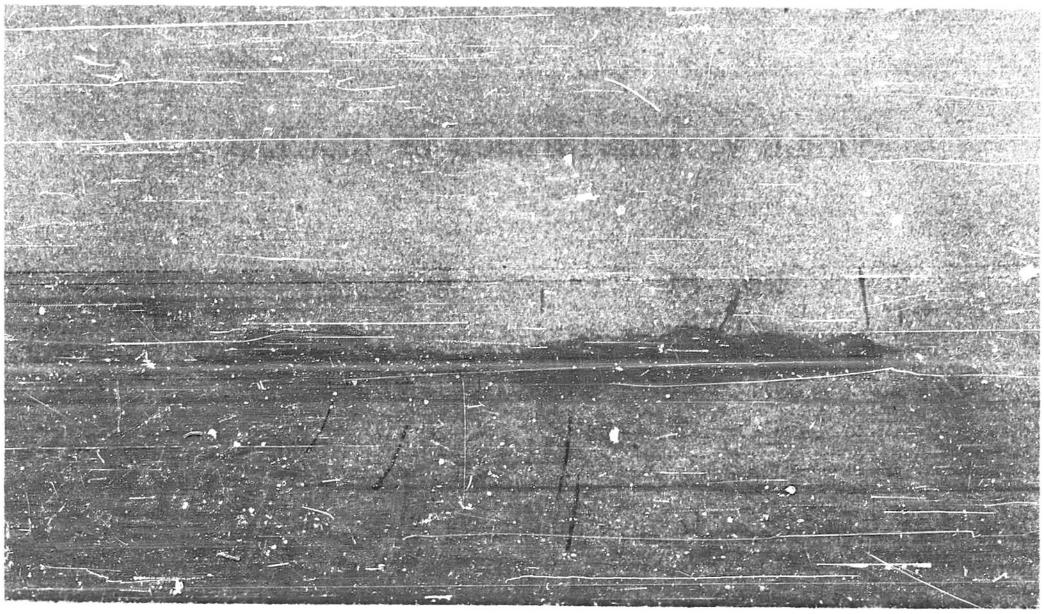
FIG. 5

CRATERS FORMED BY 4200 LB CHARGES ON SANDY CLAY



SHOT NO. 311 CHARGE ON BOTTOM WATER DEPTH 1.00 FT

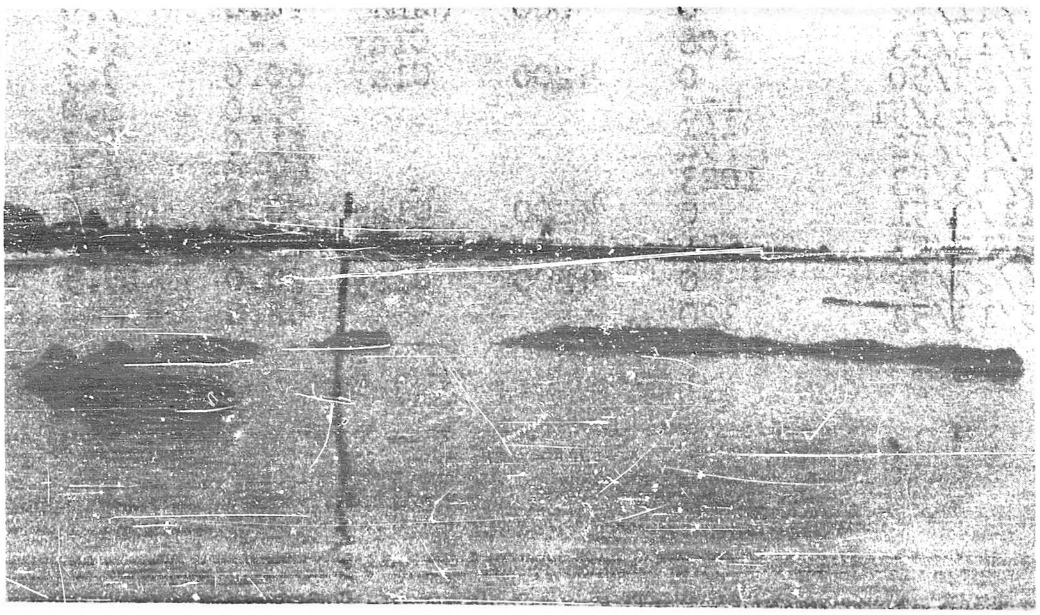
FIG. 6 CRATER FORMED BY 100 LB CHARGE ON SAND



SHOT NO. 281
CHARGE WT 4200 LB

WATER DEPTH 2.17 FT
CHARGE ON BOTTOM

49 DAYS AFTER FORMATION



SHOT NO. 272
CHARGE WT 600 LB

WATER DEPTH 3.42 FT
CHARGE ON BOTTOM

86 DAYS AFTER FORMATION

FIG. 7 EROSION OF CRATER LIPS

TABLE V PERSISTENCE OF CRATERS

Shot No.	Date	No. of Days after Explosion	Charge Weight W (lb)	Soil Type	Crater Width w (ft)	Crater Depth d (ft)	Lip Height h (ft)
271	5/23/52	0	600	Clay	40.5	5.8	4.3
	8/15/52	84			38.0	5.1	3.9
272	5/21/52	0	600	Clay	40.7	4.3	4.5
	8/15/52	86			39.0	4.8	4.0
	5/13/53	357			40.0	3.4	2.0
282	7/1/52	0	600	Sandy	34.0	7.5	1.5
	5/13/53	316		Clay	--	0.5	0
283	7/7/52	0	600	Sandy	30.0	6.0	1.2
	5/13/53	310		Clay	--	1.0	0
284	7/11/52	0	600	Sandy	28.0	7.0	2.0
	5/13/53	306		Clay	--	0.5	0
114	7/25/50	0	4200	Clay	60.0	9.5	7.0
	11/13/51	476			56.0	8.0	0.8
	8/15/52	752			51.0	6.7	0.3
	5/13/53	1023			44.0	6.1	0
218	11/9/51	0	4200	Clay	70.0	14.0	6.0
	5/13/53	551			67.0	>9.2	1.8
281	6/27/52	0	4200	Clay	70.0	15.5	4.0
	5/13/53	320			62.0	--	0.9

1.5 Discussion of Results. In underwater [1,2,3] and underground [4] explosion programs it has been generally found that a large number of shots are needed in order to obtain reliable relationships between crater size and the independent variables such as charge weight, charge depth, water depth, and type of soil. A high degree of scatter is to be expected in crater measurements, and is probably due primarily to the lack of homogeneity of soils.

The measurements of crater width, crater depth, and lip height for bottom shots on clay and sand are plotted as functions of scaled charge depth in Figures 8, 9 and 10. There is obviously considerable dispersion of the data, and the results are considered to be inadequate for the formulation of numerical scaling laws.

However, certain trends can be observed, which are consistent with results obtained in other investigations.

Crater diameter increases with increasing water depth when charges are exploded on the bottom. Although Figure 8 indicates a decrease in crater diameter for 100 lb charges at scaled depths greater than 0.522 ft/lb$^{1/3}$, this trend is probably not real. More complete data obtained by Eldridge and Fye [2] at Woods Hole and by Johnson and Chinn [3] at the University of California show that crater diameters from bottom explosions increase with water depth, at least to a scaled charge depth of 4.0 ft/lb$^{1/3}$.

There is some tendency for crater depths to increase with increasing water depth when charges are fired on the bottom, though this effect appears to be slight. It has also been observed by Eldridge and Fye [2] and Johnson and Chinn [3] for charges fired within the same range of scaled depths on sand.

Lip heights show considerable scatter and it is probably impossible to draw any conclusions from the data presented herein, though data presented by Johnson and Chinn [3] show an increase in lip height with increasing water depth for 1 lb charges fired at the same range of scaled depths on sand bottoms.

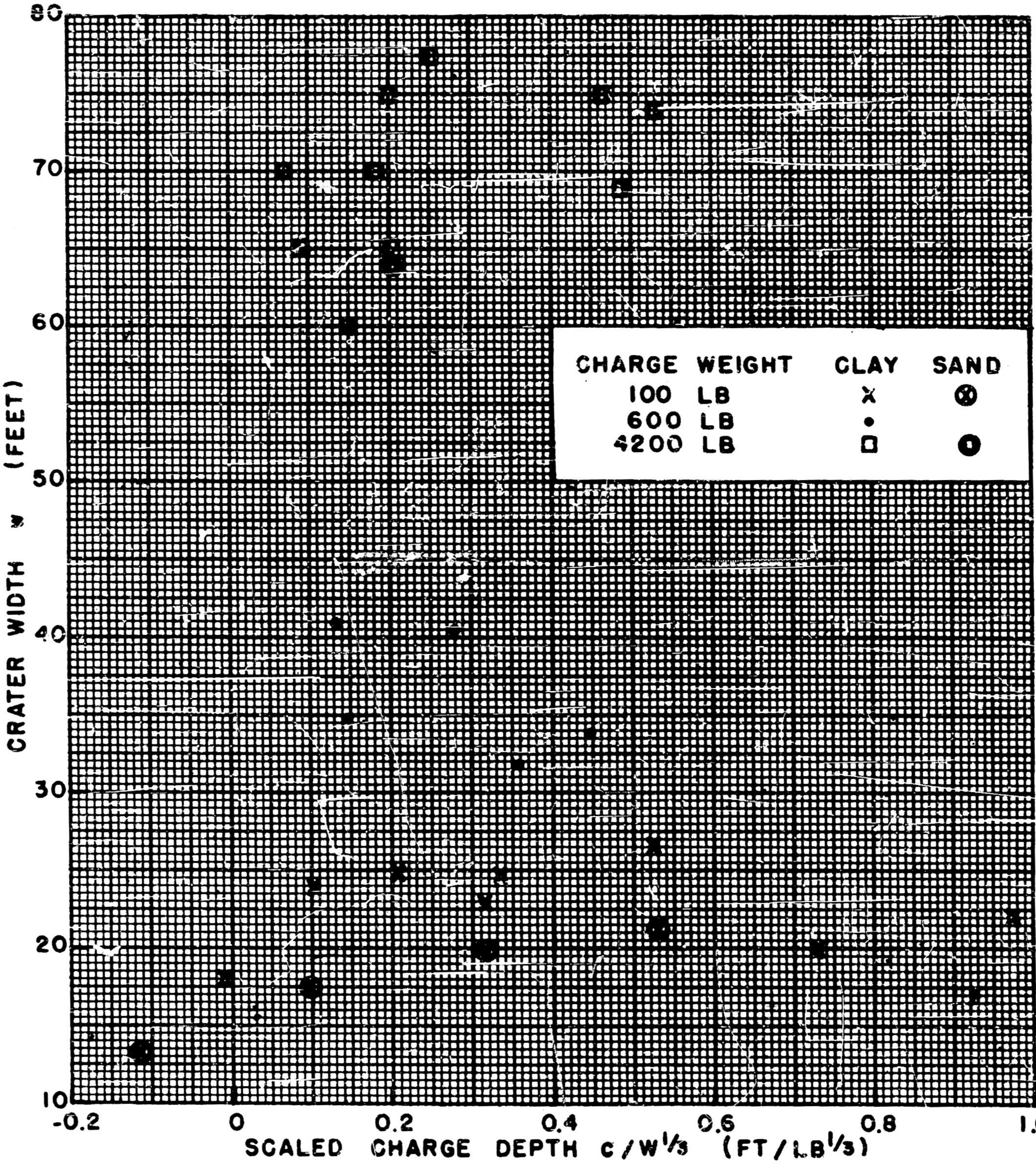


FIG. 8 CRATER WIDTH vs SCALED CHARGE DEPTH FOR EXPLOSIONS ON CLAY AND SAND

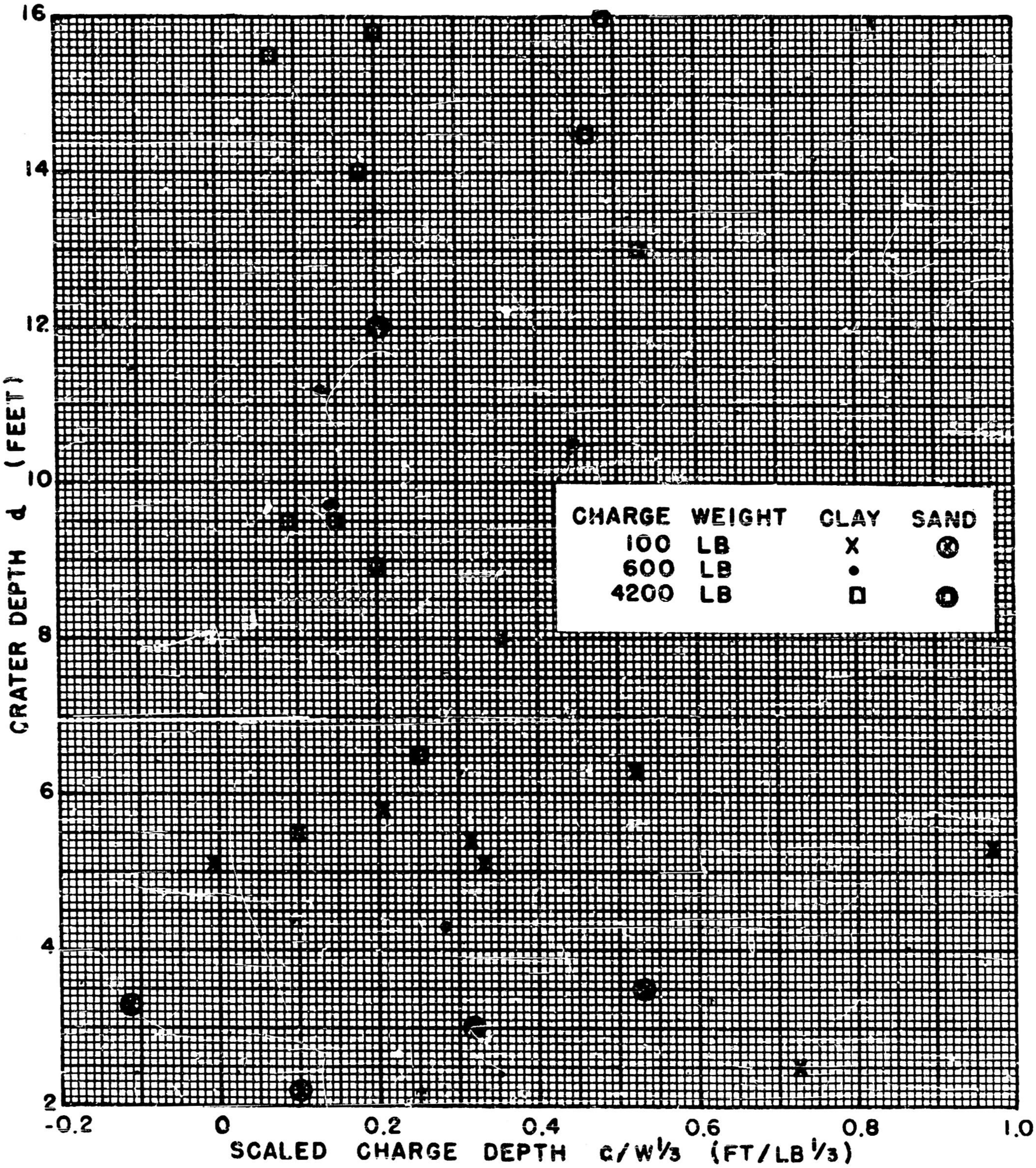


FIG. 9 CRATER DEPTH vs SCALED CHARGE DEPTH FOR EXPLOSIONS ON CLAY AND SAND

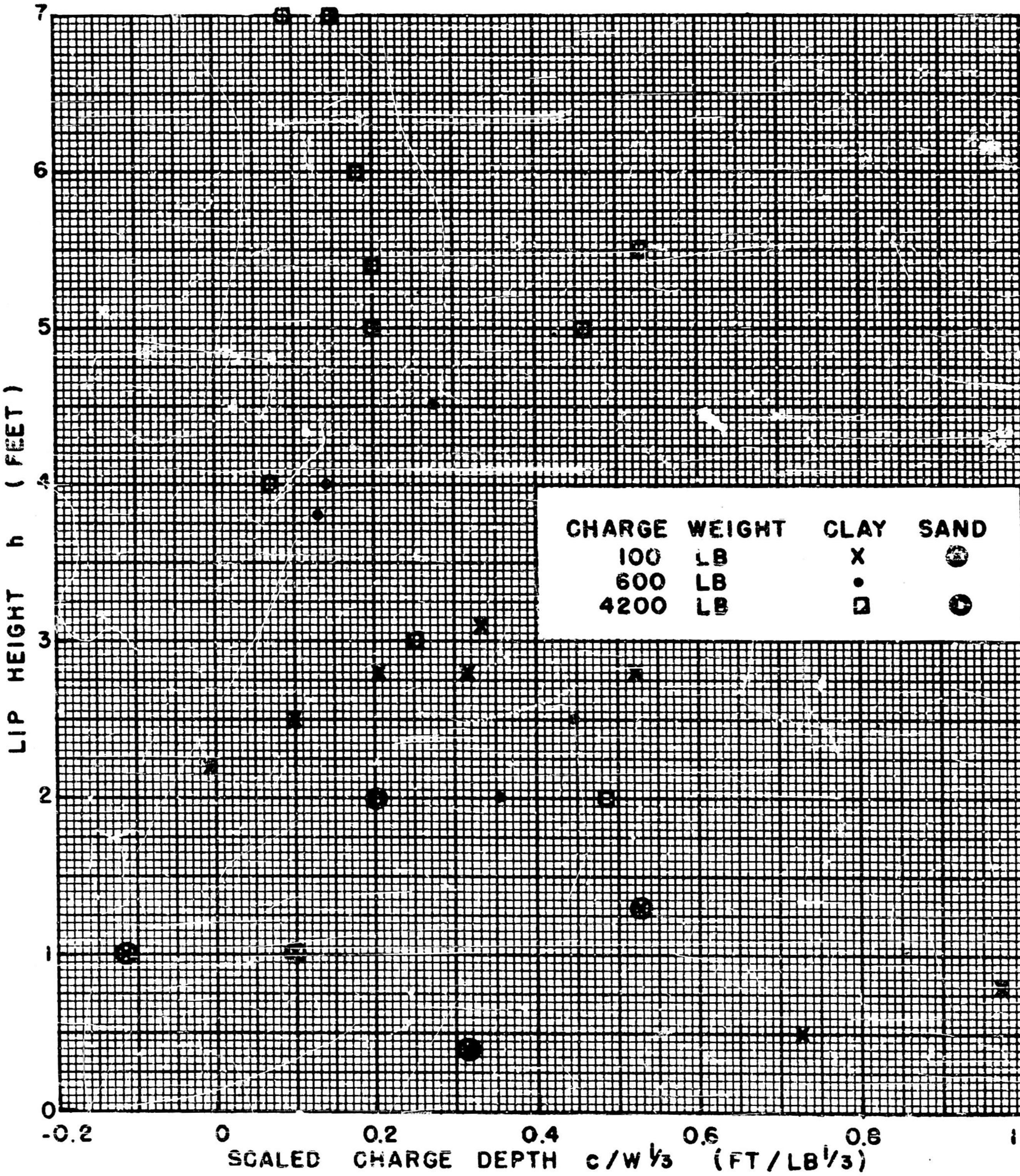


FIG. 10 LIP HEIGHT vs SCALED CHARGE DEPTH FOR EXPLOSIONS ON CLAY AND SAND

The data in Table I indicate the formation of shallower craters with greater diameters when charges are fired on platforms at approximately mid-depth instead of on the bottom, an effect also observed at Vicksburg[1] and the University of California[3] with charges fired on sand at similar scaled depths. The lip height data tend to show that bottom shots form higher lips than platform shots.

The data are not adequate to show the effect of charge burial on crater size, though experiments in sand at Vicksburg[1] and the University of California[3] have shown an increase in all crater dimensions with shallow burial of the charge.

Craters are wider, deeper, and have higher lips in clay than in sand, an effect also observed in studies of underground explosions.[4] It is generally observed that sand craters collapse and fill in quite rapidly after an explosion and the values obtained depend somewhat upon the time elapsing between the explosion and the measurement. It is probably impossible to distinguish between the real and apparent craters underwater, as is often done in studies of cratering by underground explosions in order to evaluate the amount of crater fill-in.

If the attempt is made to determine crater dimensions as a function of charge weight from these data, inconsistencies may be obtained because of differences in charge shape. The 100 lb charges were cubical in shape and the 600 lb charges were cylinders with height and width approximately equal. However, the 4200 lb charges were about 3 times as wide as they were high and do not scale geometrically to the smaller charges. The 4200 lb charges fired on the bottom have a proportionately greater amount of water above them than the smaller charges at the same scaled depth and may form craters larger in size than would be expected from cubical or spherical charges of the same weight.

CHAPTER II

BOTTOM CHARACTERISTICS AT DAHLGREN

2.1 Soil Tests. At the request of the Waterways Experiment Station, four samples of the clay from the crater formed by Shot 285 and one sample of the sandy clay in the area used for Shots 293, 294, and 295 were forwarded to Vicksburg for analysis.

The water content of each sample was determined and Atterberg limits and shear strength tests were performed on three of the samples. The results of the tests are presented in Table VI.

TABLE VI

RESULTS OF TESTS ON SOIL SAMPLES

Sample	Soil Type	Water Content (% dry weight)	Atterberg Limits LL (%)	PL (%)	PI	Dry Weight (lb/ft^3)	Cohesion (lb/ft^2)
1	Clay	94	107	31	76	47	102
2	Clay	88					
3	Clay	82	103	30	73	51	114
4	Clay	86					
5	Sandy Clay	56	61	25	36	63	62

The liquid limit (LL) is defined as the highest moisture content at which the soil can be readily molded and retains its shape. With additional water content, the soil has the capacity to flow as a liquid. At moisture contents below the plastic limit (PL) the plastic properties are lost and the soil crumbles when worked. The liquid limit thus defines

the border between liquid and plastic states of the soil, and the plastic limit defines the border between the plastic and semisolid states.[5]

The difference, (LL-PL), is the plasticity index (PI) of the soil. The values of 76 and 73 shown in Table VI indicate the exceptionally high plasticity of the Dahlgren clay.

2.2 Stratification of Soils. At the request of the U. S. Naval Radiological Defense Laboratory, the Chesapeake Bay Institute obtained core samples of the river bottom in the firing area at Dahlgren during March 1953.[6] Cores were taken from the undisturbed area around the craters and the bottoms and lips of the craters. The area investigated included the craters from Shots 293 to 300, where the bottom had been designated mainly as sandy clay.

In the undisturbed area around the craters the dominant material was fine sand with some coarse sand and gravel but no fine silt or clay. It was estimated that this surface layer was about two feet deep.

The surface material in the bottoms of the craters contained appreciable amounts of clay, although the predominant size class was very fine sand.

The sediment on the lips of the craters showed a relatively high clay content, averaging about 23%.

It was estimated that a layer of plastic muddy sand with appreciable quantities of fine silt and clay lay beneath the surface layer of sand. This layer of plastic sediment appeared to be about four to five feet thick. A sandy sediment similar to the surface layer probably existed beneath this.

The Chesapeake Bay Institute concluded that the effect of an explosion on the sediment distribution was to clean off the surface sand and cause the plastic sub-layer to deform and bulge upward, extending well above the level of the undisturbed surface sand layer. Due to its high clay content, the soil that bulged upward to form the crater lips was resistant to erosion.

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